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Investigation of Annular-Two Phase Flow, and Heat Transfer to and from Gases with Large Temperature Differences

by

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Summary Report of Investigations of
Annular-Two Phase Flow, and
Heat Transfer to and from Gases with Large
Temperature Differences

Introduction

This report is a summary of the investigations concerned with (A) Annular Two-Phase Flow and (B) Heat Transfer to and from Gases with Large Temperature Differences. The report is presented in two separate sections concerned with topics (A) and (B).

(A) A Summary of Two-Phase Annular Flow Investigations Conducted at the Purdue Jet Propulsion Center

Introduction

This section presents a summary of the investigations of two-phase annular flow conducted at the Jet Propulsion Center of Purdue University with primary emphasis on the portion of the program conducted during the period 1 October 1959 to 1 February 1961. The material presented here was obtained from the theses of A. B. Greenberg, D. A. Charvonia, and H. H. Ammann.*

The stimulus for this investigation arose from a study of the liquid film cooling of rocket motors at the Jet Propulsion Center. In that application the inner walls of a tube containing high temperature combustion gases are protected by interposing a thin film of liquid between the gas and the wall. In the application of liquid film cooling the following information is of importance: (a) the quantity of liquid required, (b) the most effective means of applying the liquid coolant, and (c) the physical properties which define the most satis-

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* See references at the end of this report.

factory coolant. Liquid film cooling also appears attractive for cooling the confining surfaces of certain types of plasma jet motors.

Object of Research Program

The subject investigation was initiated to obtain a basic understanding of the physical phenomena associated with annular two-phase flow. The specific objectives of the research program reported herein were to obtain an understanding of the influence of the flow rates of the two fluid media upon the mean thickness of the liquid film and to investigate the characteristics of the interfacial surface between the gas and liquid film.

The experimental studies were made employing vertical glass tube as the test section with downward flow of the liquid film. All of the experiments were conducted at ambient temperatures and pressures to reduce the complications introduced by the effects of heat and mass transfer between the liquid and gaseous phases. The effect of the viscosity of the liquid upon the flow characteristics of the liquid film interface was also considered.

The investigation was divided into three principal phases (a) a literature survey, (b) an experimental investigation, and (c) an analytical study. The results of the literature survey have been reported by Charvonia in reference 1. The results of the experimental and analytical investigations are reported in references 2, 3, and 4.

Review of Accomplishments

To make a detailed experimental study of the mean film thickness and characteristics of the gas-liquid interface in the annular two-

phase flow a new experimental technique had to be developed. A unique photometric technique was developed by Greenberg (3), and extended by Charvonia (2), to measure accurately the mean film thickness, as well as the instantaneous total thickness of the film at a point. This latter feature made it possible to actually obtain profiles of the gas-liquid interface from which a statistical distribution of the wave amplitude vs. frequency for various flow conditions could be made.

The photometric technique was based on the fact that the amount of light-absorbing medium is related to the thickness of that medium by Lambert's Law, which states that

$$T = \frac{I}{I_o} = e^{-kt}$$

where

T = transmission of light

I_o = intensity of the incident light, lumens/ft^2

I = intensity of light after passing through the absorbing medium, lumens/ft^2

K = absorption coefficient of the medium/ft and

t = thickness of the medium, ft.

In the experimental investigation, a beam of light of known intensity was passed diametrically through the glass tube comprising the test section. Inside the test section the liquid film was divided at the spot where the light beam entered the test section. In this way the light beam passed only through the walls of the glass tube and through one thickness of film. From the measured intensity of the transmitted light with the absorbing medium in the tube, and the intensity of the transmitted light without the absorbing medium in the tube, the mean film thickness could be determined from Lambert's Law. In order to be able to detect small variations in film thickness the absorption coefficient of the liquid must be large. This was accomplished by adding a small amount of Nigrosene dye to the test liquid.

The intensity of the light transmitted through the test section was measured by means of a photomultiplier tube. The photomultiplier tube was operated in its linear region so that the signal output was directly proportional to the light flux. For this reason the intensity ratio in Lambert's Law could be replaced by the tube signal ratio for determining the mean film thickness.

The output of the photomultiplier tube could be directed through a D.C. microammeter either to a cathode ray oscilloscope or to a pair of

electronic counters connected in parallel. The microammeter was employed to determine the mean film thickness, the oscilloscope was employed with a camera to record a photographic record of the film profile, and the electronic counters were employed to determine the frequency-amplitude spectra of the interfacial disturbances.

In the subject investigation, a thin film of liquid (water) was injected radially at low velocity into the vertical glass test section (2.498" dia. x 28" long.). A stream of air could also be passed through the center of the liquid annulus in a downward direction. The single-phase apparatus employed by Greenberg was similar in principle with the exception that no provision was made for passing a gas stream through the liquid annulus.

The experimental investigation of Greenberg (3) was concerned with single-phase film flow and consisted of the following:

A. Measurement of mean film thickness.

B. Taking photographic records of the oscilloscope trace corresponding to the profile of the liquid film profiles.

C. A study of the effect of the variation of the physical properties of the liquid upon the mean film thickness.

The experimental investigation of Charvonia was concerned with two-phase film flow and consisted of the following:

A. Measurement of mean film thickness.

B. Taking photographic records of the oscilloscope trace corresponding to the profile of the gas-liquid interface.

C. A detailed statistical investigation of the relationship between the amplitude of the interfacial waves and their respective frequencies.

D. A preliminary study of the loss in static pressure of the gas stream resulting from friction with the rough surface of the liquid film.

Charvonia (2) developed an analytical method for calculating the mean liquid film thickness and the pressure drop in the gaseous stream from the rates of flow of the liquid and gaseous media, the physical properties of the fluid media, and the diameter of the duct. The analysis is based upon a physical model in which a thin film of liquid flowing over the surface of a vertical flat plate is subjected to a shear stress along its free surface by a gaseous stream moving at a high velocity. The results obtained from the afore-mentioned physical model are then applied to the case of annular, two phase flow in a vertical pipe. For the purpose of the analysis, it is assumed that the flow of both fluid media is steady, incompressible and isothermal, and that surface tension forces are negligible. An empirical correlation

was obtained from the investigation which relates a fictitious gas friction coefficient to the mean liquid film thickness.

Charvonia (2) reached the following conclusions from his investigation.

1. An analytical method was developed relating the mean liquid film thickness and pressure drop in the gaseous stream to the flow rates of the fluid media, the physical properties of the fluid media, and the duct diameter.
2. The mean liquid film thickness increases with an increase in the peripheral liquid flow rate at a constant gas velocity; it decreases with an increase in the gas velocity at a constant peripheral liquid flow rate.
3. For operation within the region of disturbance instability* and at gas velocities exceeding 100 fps, the mean liquid film thickness is less than 0.010 in. (for air and water as the liquid media).
4. The pressure gradient in the gas stream in annular, two-phase flow exceeds that in a smooth tube at the same gaseous Reynolds number for gas velocities greater than some minimum value; specific values of the latter depend upon the peripheral liquid flow rate.

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* Disturbance instability is defined as a liquid flow condition where crests of the interfacial waves on the free surface of the liquid film are torn off and carried into the gas stream in the form of droplets.

5. The pressure gradient in the gas stream increases with an increase in the peripheral liquid flow rate at a constant velocity in the region of disturbance stability; for similar conditions, however, the pressure gradient in the gas stream increases more rapidly in the region of disturbance instability.

6. The amplitudes and frequencies of the interfacial disturbances display a definite spectra for given rates of flow of the two fluid media; these spectra characterize the structure of the gas-liquid interface.

7. A method has been developed for defining the zone between the regions of disturbance stability and disturbance instability. The lower limit of this zone is defined by the flow of the liquid phase while the upper limit is defined by the flow of the gaseous phase.

During the period 1 October 1959 to 31 September 1960, Ammann (4) conducted an experimental investigation to substantiate Charvonia's analysis for liquids having a high viscosity, i.e., about ten times the viscosity of pure water (4). The test liquid employed was a mixture of 54% glycerol and water. This mixture had the desired high viscosity, while the density and surface tension were of the same magnitude as those of pure water.

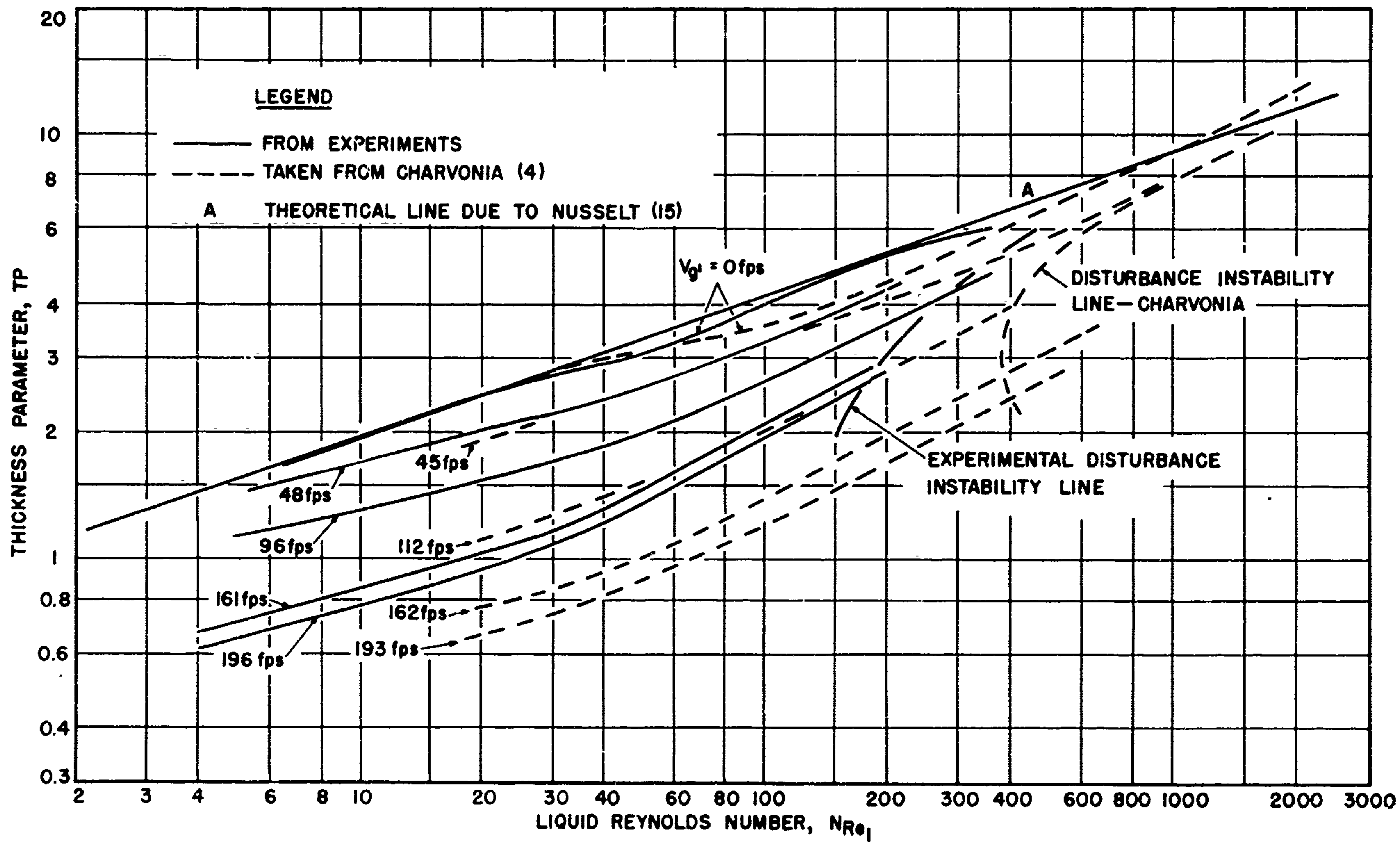

FIG. 1 COMPARISON BETWEEN EXPERIMENTAL VALUES OF THICKNESS PARAMETER AS A FUNCTION OF THE LIQUID REYNOLDS NUMBER FOR TWO DIFFERENT TEST LIQUIDS

The experimental investigation of Ammann consisted of:

(1) The measurement of the mean film thickness for air velocities ranging from 0 to 200 fps with liquid Reynolds numbers ranging from 5 to 400.

(2) The determination of the flow conditions under which disturbance instability first occurs.

(3) Study of the interfacial profile for the full range of flow conditions and a comparison of the results with the profiles obtained by Charvonia (2) who employed water as the test liquid.

Ammann (4) found that under experimental conditions similar to those employed by Charvonia (2) the curves of thickness parameter versus liquid Reynolds number were quite similar in shape to those of Charvonia, (see Fig. 1) but shifted up and to the left of those obtained by Charvonia. The "disturbance instability line" obtained by Ammann, Fig. 1, also lies to the left of that obtained by Charvonia, indicating that when the film is made from a more viscous fluid the droplet entrainment occurs at a lower Reynolds number. Since the Reynolds number of a liquid varies inversely with its viscosity, it was found that disturbance instability for the more viscous liquid occurred at a higher liquid weight flow rate.

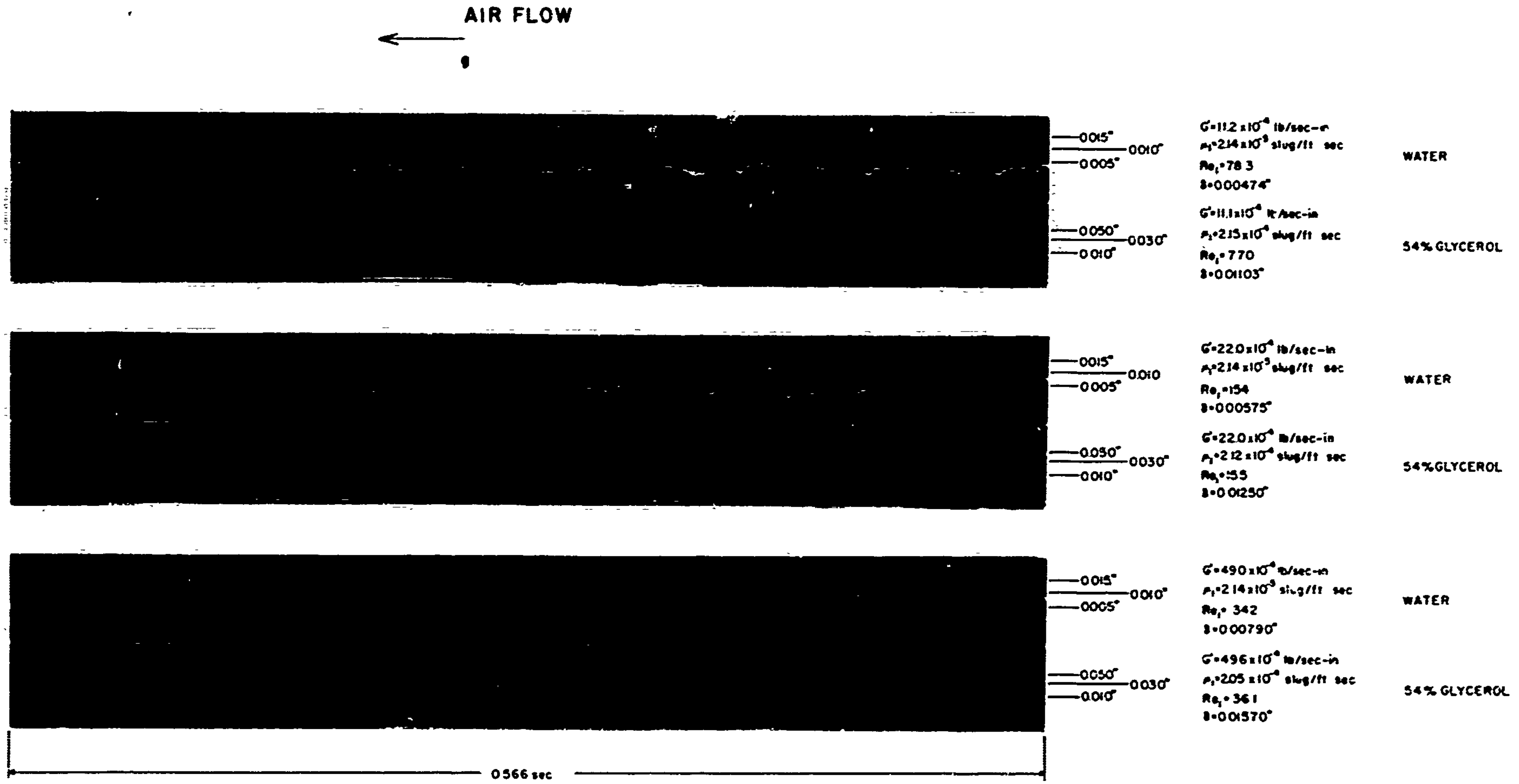

FIG. 2 COMPARISON OF WAVE PROFILES: 54% GLYCEROL-WATER VS WATER, $V_g' = 73$ FT/SEC

This was to be expected since an increase in the viscosity of the liquid tends to damp out the interfacial disturbances which incite droplet entrainment.

The experimental results of Ammann (4) were in closer agreement with those corresponding to Nusselt's analysis (1) than the experimental results of Charvonia (2). This can possibly be explained by the fact that the flow of the more viscous fluid of Ammann (4) more closely approximates the laminar flow assumed by Nusselt (1).

The photographic records of the ocillographic trace corresponding to the profile of the gas-liquid interface obtained by Ammann (4) (see Fig. 2) indicate that for equal liquid flow rates a much higher air velocity is required to produce a significant number of high frequency waves on the gas liquid interface with the glycerol-water test solution than for water. It is also evident from Fig. 2 that the waveform of the interfacial waves is different for the two test liquids.

The results of the investigation of Ammann are summarized below.

1. For a given air velocity, increasing the viscosity of the liquid forming the films increases the mean liquid film thickness for the same liquid flow rate.
2. Correlation of the data by plotting the thickness parameter, TP, vs. liquid Reynolds number, N_{Re_l}, is reasonably satisfactory for a large variation in the viscosity of the liquid.

3. Increasing the viscosity of the liquid in the film improves the film stability.

Notation

$$N_{Re_l} = \frac{4G'}{g} \qquad (1)$$

$$T.P. = \delta\left[\frac{1}{g}\left(\frac{\gamma_l}{\mu_l}\right)^2\right]^{1/3} \qquad (2)$$

where

G' = peripheral liquid flow rate, lb /sec-ft

μ_l = liquid viscosity slug/ft-sec

g = gravitational constant, ft/sec^2

γ_l = liquid specific weight lb /ft^3.

δ = mean film thickness, ft

N_{Re_l} = liquid Reynolds number

TP = thickness parameter

Vg' = fictitious value of the average gas velocity assuming zero film thickness, ft/sec.

(B) A Summary of Studies of Heat Transfer to and from Gases With Large Temperature Differences

Introduction

The ever-increasing importance of high speed aircraft, missiles, and space vehicles propelled by air breathing or non-air breathing jet propulsion devices producing thrust from high temperature, high velocity gases has brought continued demands for increased performance of the propulsion systems. The latter can in general be best achieved by increasing the temperature of the working fluids. One of the major problems in the design of such propulsion systems involves the consideration of the energy released by the high temperature gases as they flow through the engine.

Problems of a similar nature are encountered in the design of gas-cooled nuclear reactors for nuclear rocket and space power systems. Although the direction of energy flow is away from the surface as compared to toward the surface as in jet porpulsion engines, the basic problem of heat transfer with large temperature differences between the gas and the wetted surface remains. The need for accurate experimental and analytical investigations in the field of heat transmission that are applicable to the afore-mentioned conditions is apparent.

The geometric configuration which has the widest application in the propulsion field is that of flow in a circular duct. Experimental studies of heat transfer to and from gases flowing in tubes was initiated at the Jet Propulsion Center, Purdue University in October 1951 under the sponsorship of Project SQUID, Contract N 6 ori-105, T.O. III, Phase 11. The investigations were continued under Contract N-onr-1858(25) until October 1958. During the period November 1, 1958, until February 1961 the research program was sponsored directly by the Office of Naval Research under Contract N -onr-1100(14).

Review of Studies Conducted Prior to October 1958

The studies conducted under the sponsorship of Project SQUID were performed to obtain information as to (a) the heat transfer coefficients for both heating and cooling of gases in turbulent flow inside tubes with large temperature differences between the gas and the tube; and (b) the development of analytical expression relating the heat transfer coefficients to the pertinent physical properties of gases and the flow parameters.

The forced convective heat transfer coefficients of gases flowing turbulently in round tubes were determined experimentally under the following conditions:

Cooling Studies

Parameter	Range
Gas	Air, CO_2, He
Bulk Reynolds number	16,500 to 152,000
Inlet gas bulk temperature	67 5 to 2200 R
Constant tube wall temperature	640 to 1900 R
Tube wall axial temperature gradient	-20, 0, +12, R/in.
Gas pressure	50 to 350 psia
Tube length/diameter	40, 60

Heating Studies

Gas	Air, CO_2
Bulk Reynolds number	44,200 to 280,000
Average tube wall temperature	1016 to 1780 R
Average gas bulk temperature	504 to 808 R
Gas pressure	100 psia
Tube length/diameter	20, 40, 60

Extensive analytical studies of heat transfer in tubes were conducted in conjunction with the experimental investigations.

The results of the investigations have been published in the semi-annual Project SQUID reports, and by Katz, Botje, and Wolf in the References presented at the end of this section.

Wolf (7) concluded that the heat transfer coefficients for the case of a hot gas flowing through a cooled tube (cooling) could be correlated within ± 7 by the relationship

$$\overline{Nu}_b = 0.0202\ \overline{N}_{Re_b}^{0.8}\ \overline{N}_{Pr_b}^{0.33} \tag{1}$$

where $\overline{Nu}_b$ = average Nusselt number with physical properties evaluated at the bulk temperature of the gas

$\overline{N}_{Re_b}$ = average Reynolds number with physical properties evaluated at bulk temperature of the gas.

$\overline{N}_{Pr_b}$ = average Prandtl number with physical properties evaluated at bulk temperature of the gas.

Equation 1 was obtained employing a test section having an L/D of 60 under conditions of constant tube wall temperature. It should be pointed out also that variations in the ratio of gas bulk temperature to tube wall temperature had no noticeable effect upon the data when correlated by equation 1.

The data for the case of a cold gas flowing through a heated tube (heating) obtained by Wolf were correlated within $\pm$ 5 per cent by the relationship

$$\bar{j}_f = 0.00406\ \bar{N}_{Re_f}^{-0.2}\ (T_w/T_b)^{-0.55}\ (L/D)^{-0.15} \qquad (2)$$

where

$\bar{j}$ = average Colburn j factor with physical properties evaluated at film temperatures.

$\bar{N}_{Re_f}$ = average Reynolds number with physical properties evalauted at film temperatures.

T_w = tube wall temperature

T_b = gas bulk temperature

L = test section length

D = test section diameter.

Variations in gas pressure were found to have no observable effect upon the heat transfer coefficient.

Results of Studies Conducted During the Period 1 Nov 1958 to 1 Feb 1962

The heat transfer studies were continued by Fowler (10) (11), and Chu (12), and M. L'Ecuyer during the period 1 November 1958 to 1 February 1961. In the studies of Fowler and Chu the heat transfer characteristics of hydrogen for the case of gas heating were investigated.

It was found that the average heat transfer coefficients for hydrogen over the range of gas bulk inlet temperatures from -100 F to 500 F could be correlated within ± 5 per cent by the relationship

$$\bar{N}u_b = 0.0207\ (\bar{N}_{Re_b})^{0.8}\ (\bar{N}_{Pr_b})^{0.4}\ (\bar{T}_w/\bar{T}_b)^{-0.3} \qquad (3)$$

The data correlated by equation 3 was obtained at Reynolds numbers above 9000 employing a heat test section having an L/D of 40. The range of variables encompassed in the investigation is presented in Table 1.

Table 1

Range of Variables Covered in the Experiments with Hydrogen

Average bulk Reynolds number	3,670	-	80,000
Average tube wall temperature, R	592		1,573
Average gas bulk temperature, R	60		701
Bulk inlet temperature, R	360		559
Static pressure in test section, psia	40		100
Heat flux at tube wall, B/in.^{2}sec	0.051		0.965

For the case of gas heating, values of the half-Fanning friction factor for hydrogen were found to be unaffected by changes in bulk temperature of the gas and were in agreement with the Karman-Nikuradse

line for the case of isothermal flow.

All of the data for the case of heating of the gas were obtained under the condition of constant heat flux in the axial direction of the test section. As a consequence there existed a temperature gradient of the tube wall in the axial direction. When analyzing his data, Wolf (3) indicated that the tube wall temperature gradient had a definite effect on the amount of energy transferred from the tube to the gas. He also applied the theory developed by Rubesin for a flat plate to calculate the percentage of the total heat transferred from the tube to the gas which could be attributed to the wall temperature gradient. It was desired to obtain an experimental verification of Wolf's theoretical analysis.

The tube, employed as the test section, is an electrical resistance heating element. Thus the local heat flux can be varied by varying the tube resistance in the axial direction. The resistance of a new tube was altered by varying the annular cross-section area of the tube. This was accomplished by grinding a taper on the O.D. of the tube.

With the tapered tube, overall heat transfer data from the heated tube to air were obtained for a constant wall temperature of 600 F over an 18 inch

length over a range of Reynolds numbers from 33,000 to 220,000. That data were compared to the data obtained by Wolf at the same integrated average wall temperature under the condition of constant heat flux. No appreciable differences in the data could be found.

Distribution

Distribution of this report has been made in accordance with the Joint Army-Navy-Air Force Liquid Propellant Mailing List of November 1960.

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